Determination of Orthometric Heights Using DGPS

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1.0 INTRODUCTION

In 1997 the Florida Department of Transportation (FDOT) approved a University of Florida (UF) research proposal to explore improving the determination of orthometric heights using the Global Positioning System (GPS). Leland Burton was appointed as the FDOT technical program representative. The research plan included two major components:

1. Evaluate the precision of GEOID96 over Florida and investigate possible places for improvement.
2. Develop and test simplified guidelines for the observation of ellipsoid heights using GPS.

The evaluation of the existing, and generation of an improved, geoid model required access to specialized computer programs and gravity anomaly data. The UF approached the National Geodetic Survey (NGS) and the National Imagery and Mapping Agency (NIMA), and these agencies agreed to work cooperatively. NGS agreed to provide computer software, training for UF personnel, and access to the NGS gravity data base. The National Imagery and Mapping Agency (NIMA) agreed to make gravity anomaly data available from their data base.

This report reviews the work performed to improve the *gravimetric* geoid model and the development and testing of guidelines for the use of GPS to obtain ellipsoid heights of adequate accuracy to be combined with the geoid model to derive orthometric heights accurate to 2 to 5 cm.

2.0 IMPROVEMENT OF THE FLORIDA GEOID MODEL - PHASE 1

2.1 Global Geoid Model

The development of a regional gravitational geoid model first requires the development or adoption of an existing global model. Today global geoid models are based on a combination of satellite tracking observations, satellite altimetry observations and surface gravity observations. The undulations of the geoid, relative to a reference ellipsoid, are usually expressed in the form of a spherical harmonics series. The spatial resolution R of the spherical harmonics series is approximately equal to 20,000km / Nmax, where Nmax is the maximum degree of the series. The most prominent recently released global geoid model is the Earth Gravity Model, 1996, designated EGM96 (Figure 1). It is the result of three years of intensive work by some two dozen collaborating scientists at the NASA Goddard Space Flight Center (GSFC), the National Imagery and Mapping Agency (NIMA) and the Ohio State University (OSU). EGM96 was used by NGS in the computation of GEOID96 and it will likely be several years before a significantly more accurate global geoid model is developed.

EGM96 is complete through degree and order 360, which results in a spatial resolution of approximately 55 kilometers. Comparison of EGM96 with GPS/leveling geoid heights over the US have a standard deviation of 43 centimeters, suggesting that there could still be regional distortions of EGM96 of several centimeters, perhaps a decimeter or more, in a region as large as Florida. In fact, modeling the geoid in Florida presents some special complexities because of the effects of the Gulf of Mexico, the Atlantic, and the Caribbean. The geoid changes rapidly in just those areas where the highest possible accuracy is needed, immediately along the shoreline in the most heavily developed areas of the State. Access to offshore gravity values is therefore very important and at the same time difficult and expensive to obtain, requiring measurements from ships, aircraft or satellites.

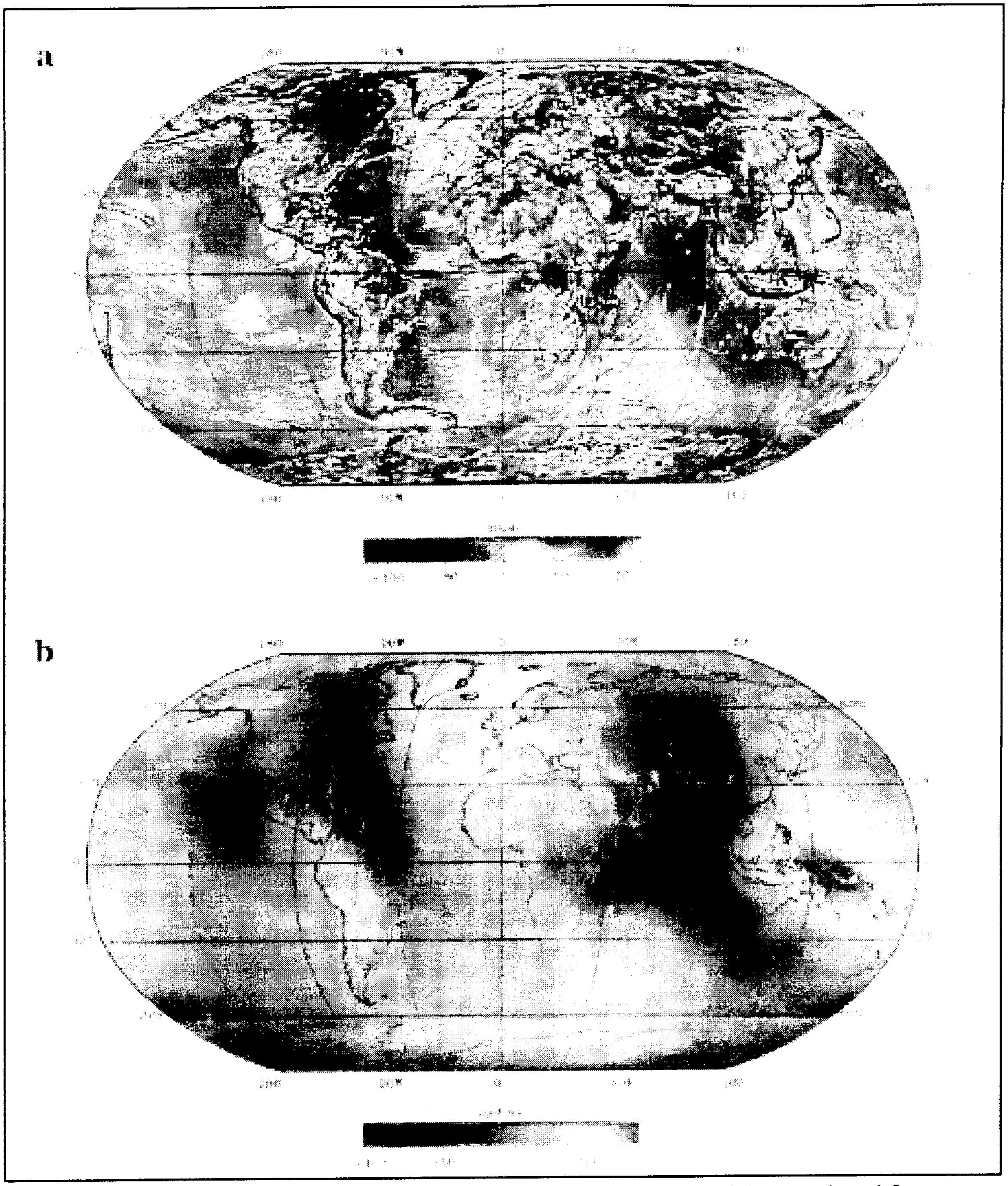

Figure 1. EGM96 (a) Gravity Anomaly Map and (b) Geoid Model, reproduced from Lemoine et. al., 1998.

2.2 Regional Geoid Model

Once a global geoid model is adopted, the Stokes' integral is used to compute improved values for the geoidal undulations (N) in the region of interest. Current practice is to use Fast Fourier Transform (FFT) remove-restore techniques to estimate the Stokes' integral within the region. The regional geoid is developed using gridded gravity anomalies, typically at spacings of a few minutes of arc. GEOID96 used a grid spacing of 2 minutes of arc. The accuracy of the anomalies depends on the availability of gravity observations and often varies greatly over an area the size of Florida. There are many factors that cause the density of gravity observations to vary, perhaps the most important being accessibility and intended applications. There is another factor that affects the availability of gravity data in Florida - the use of gravity observations for geophysical exploration, i.e., in local offshore areas that may contain deposits of oil.

The possibility of locating oil provides the economic incentive for private companies to measure gravity offshore. Unfortunately, the competition among companies has resulted in much of these data being considered proprietary and not available to academic researchers. Selected sets of these data have been made available to NGS and NIMA on a restricted basis for official governmental use, and NGS has included these data in the computation of GEOID96. However, NIMA has additional data, both from private and military sources, that were not available to NGS and were not included in the computation of GEOID96.

UF researchers had discussions with researchers at both NGS and NIMA to determine what additional data might be available in the Florida region, to determine if the additional data would significantly affect the geoid model, and if the data could be made available. The first step in this process was for NGS to provide a copy of the data set they used to compute GEOID 96 to NIMA and for NIMA to check this data set against their data holdings to determine what additional data they had. This step concluded that NIMA did have significant gravity anomaly data in the Florida region that were not included in GEOID96.

The next step was for NIMA to generate a Florida regional geoid following the same procedures used by NGS, but using the full NIMA data set. This was done for four areas, selected to represent different densities of gravity observations and different needs for accurate orthometric heights related to different applications.

Area 1 is bounded by latitudes 27 to 28 degrees north and longitudes 277.5 to 280 east. Area 1 was selected because it has an extraordinary number of gravity values available. It is near the Kennedy Space Center, NASA needed the best possible geoid model in the area for launching missiles, and a large data set of gravity observations were collected to generate the model.

Area 2 is bounded by latitudes 24.4 to 26 degrees north and longitudes 277.5 to 280 degrees east. This southern portion of Florida has relatively sparse coverage of gravity data because of the difficulty of making observations in the Everglades. However, the ongoing effort to restore the Everglades has created a need for a good geoid model to use in developing accurate hydrological models to determine the effects of modifying water management structures, such as removing dikes in the region to restore sheet flow.

Area 3 is bounded by latitudes 30 to 31 degrees north and longitudes 271.5 to 274 degrees east. Area 3 is in the panhandle of Florida and includes an area where the Florida Department of Environmental Protection has reported an apparent discontinuity in the orthometric heights computed from GPS observations when they are compared to leveling from two different bench marks. The NGS had already identified an 8 centimeter error in the geoid model in this area due to a bad gravity anomaly.

Area 4 includes the entire state of Florida bounded by 24 to 31 degrees north and 271 to 280 degrees east.

2.3 Initial Statistical Comparison between NIMA Regional Geoid Model and GEOID96

Because NIMA used classified and proprietary gravity data to generate a Florida regional geoid model UF researchers were not given access to the model itself, or even to the point by point or gridded geoid undulations. NIMA researchers compared their model and GEOID96 for the four selected test areas and computed statistical indicators of the difference between the models. These statistical indicators are given in tables 1 through 4, and include the average differences in the geoid undulations, standard deviations of the differences, the Root Mean Square (RMS) differences, the largest negative differences (value and location) and the largest positive differences (value and location).

The comparisons show an approximate 3 centimeter offset between the NIMA Florida model and Geoid 96 (Table 4). This offset is not a major concern because it would not affect the difference in orthometric heights between two points in Florida derived from GPS using the two geoid models. However, the RMS difference of approximately 10 centimeters represents the difference in the shapes of the two geoid models, which would be reflected in GPS orthometric height differences computed with the two geoid models.

The comparison in area one (Table 1), where both NGS and NIMA had the benefits of the high density of gravity data had an average difference of approximately 1.5 centimeters and an RMS difference of less than 3 centimeters, suggesting that little would be gained from further densification of gravity observations in the area. GPS determinations of orthometric heights can already be done in Area 1 with an expected error from the geoid model of a few centimeters or less.

Areas 2 and 3 have larger differences between the models than Area 1, with the Area 2 RMS difference being nearly as large as the state wide difference (Tables 2 and 3). This is most likely caused by relatively sparse data, because of the difficulty in making observations, in the Everglades and surrounding area.

We concluded from these initial comparisons between the NIMA Florida geoid and GEOID96 that the existing classified and propriety gravity data that were not included in GEOID96 would significantly change the geoid model, at the level of several centimeters, and it therefore would be beneficial to gain access to as much of those data as possible.

2.4 UF-NGS-NIMA Cooperative Agreement

Based on the initial comparisons of the NIMA Florida geoid and GEOID96 it was concluded that the next step was to have a working meeting with representatives of both organizations to attempt to develop a plan to improve GEOID96 in the Florida region.

2.5 Presentation of Project Overview and Progress

UF researchers participated in an FDOT sponsored workshop held at the UF Gainesville campus on March 11, 1998, and W E Carter summarized the status and progress of the "Determination of Orthometric Heights Using DGPS" project, focusing on the development of an improved Florida geoid model. Many of the participants expressed interest in and support of the project, and there were extensive discussions about the problems that surveyors were encountering in trying to use GPS to determine orthometric heights in Florida.

Table 1. Study Area 1

<table>
<tr><td colspan="2">Latitude: 27 - 28 N,</td><td>Longitude: 277.5 - 280.0 E</td></tr>
<tr><td>Ave (m)</td><td>-0.015</td><td rowspan="3">2,356 comparisons</td></tr>
<tr><td>Std. Dev. (m)</td><td>0.024</td></tr>
<tr><td>RMS (m)</td><td>0.029</td></tr>
<tr><td>Min (m)</td><td colspan="2">-0.132 at latitude 27.867 and longitude 279.933</td></tr>
<tr><td>Max (m)</td><td colspan="2">+0.037 at latitude 27.167 and longitude 278.600</td></tr>
</table>

Table 2. Study Area 2

Latitude: 24.4 - 26.0 N,		Longitude: 277.5 - 280.0 E
Ave (m)	-0.014	3,724 comparisons
Std. Dev. (m)	0.067	
RMS (m)	0.069	
Min (m)	-0.162 at latitude 24.533 and longitude 278.800	
Max (m)	+0.246 at latitude 24.467 and longitude 280.000	

Table 3. Study Area 3

Latitude: 30 - 31 N,		Longitude: 271.5 - 274.0 E
Ave (m)	-0.056	2,356 comparisons
Std. Dev. (m)	0.063	
RMS (m)	0.084	
Min (m)	-0.142 at latitude 30.100 and longitude 272.700	
Max (m)	+0.240 at latitude 30.200 and longitude 273.567	

Table 4. Florida

Latitude: 31 - 24 N,	Longitude: 271 - 280 E
Ave (m)	-0.030
Std. Dev. (m)	0.095
RMS (m)	0.100
Min (m)	-0.378 at latitude 27.133 and longitude 274.567
Max (m)	+0.295 at latitude 28.767 and longitude 277.133

3.0 IMPROVEMENT OF THE FLORIDA GEOID MODEL - PHASE 2

3.1 Refinement of Research Milestones

In May 1998 the FDOT technical program representative changed from Leland Burton, to Beverly Sutphin. A working meeting was held with Beverly Sutphin and Dave Brazet representing FDOT, and William Carter and Ramesh Shrestha representing UF, to review the status of the project and discuss any new guidance that Beverly Sutphin might want to provide. The following milestones were agreed to:

1. Compare the National Geodetic Survey (NGS) GEOID 96 model with a research model created by the National Imaging and Mapping Agency (NIMA) in three test areas to determine if the more extensive data set in the NIMA gravity data base would yield a significantly more accurate geoid model.

2. Obtain the NIMA evaluated gravity data set covering Florida, plus and minus 3 degrees in latitude and longitude. Identify sparse areas and request any available proprietary data that would improve the coverage.

3. UF graduate student complete training at NGS on procedures for cleansing gravity data and generating a new regional geoid model.

4. Generate an improved Florida geoid model.

5. Evaluate the new geoid model and prepare a final project report.

Based on the use of milestones to track the progress of the project, the submission of reports was adjusted to reflect completion of milestones rather than being on a quarterly basis. The goal was to complete the final report in September 1998. Because of delays in completing the joint UF-NGS geoid modeling and preparation of a technical paper, the date was later extended until June 1999.

3.2 Agreement Completed with NGS and NIMA

On April 23, 1998, UF researchers met with representatives of the National Geodetic Survey (NGS) in Silver Springs, Maryland. Dr. Richard Rapp, Ohio State University, and consultant to UF on the development of geoids, also attended the meeting. Mr. Steve Kenyon, National Imaging and Mapping Agency (NIMA) participated by teleconference in a portion of the meeting.

It was assumed at the Silver Springs meeting that it would be necessary for NGS and NIMA to modify an existing Memorandum of Understanding (MOU) and for NGS and UF to sign a new MOU. Dave Zilkoski, NGS, took an action item to prepare drafts and see that the necessary actions were completed to get the MOUs in place. However, after checking further Dave Zilkoski concluded that no MOU was needed for the NGS and UF cooperative work.

3.3 Gravity Data Obtained from NGS and NIMA

Based on the agreements reached at the Silver Springs meeting NIMA and NGS both provided gravity data covering the Florida region (3 degrees beyond the Florida borders in both latitude and longitude). The two data sets contained many of the same points, but there were points unique to each data set, with the NIMA data set having more off-shore data and the NGS having better on-shore coverage. The data sets were merged to create the best coverage. There remains a sparsely covered area along the northwest coast between 28° and 30° N latitude, 82° 40' and 84° W longitude. This area is approximately 30 km wide and 250 km long .

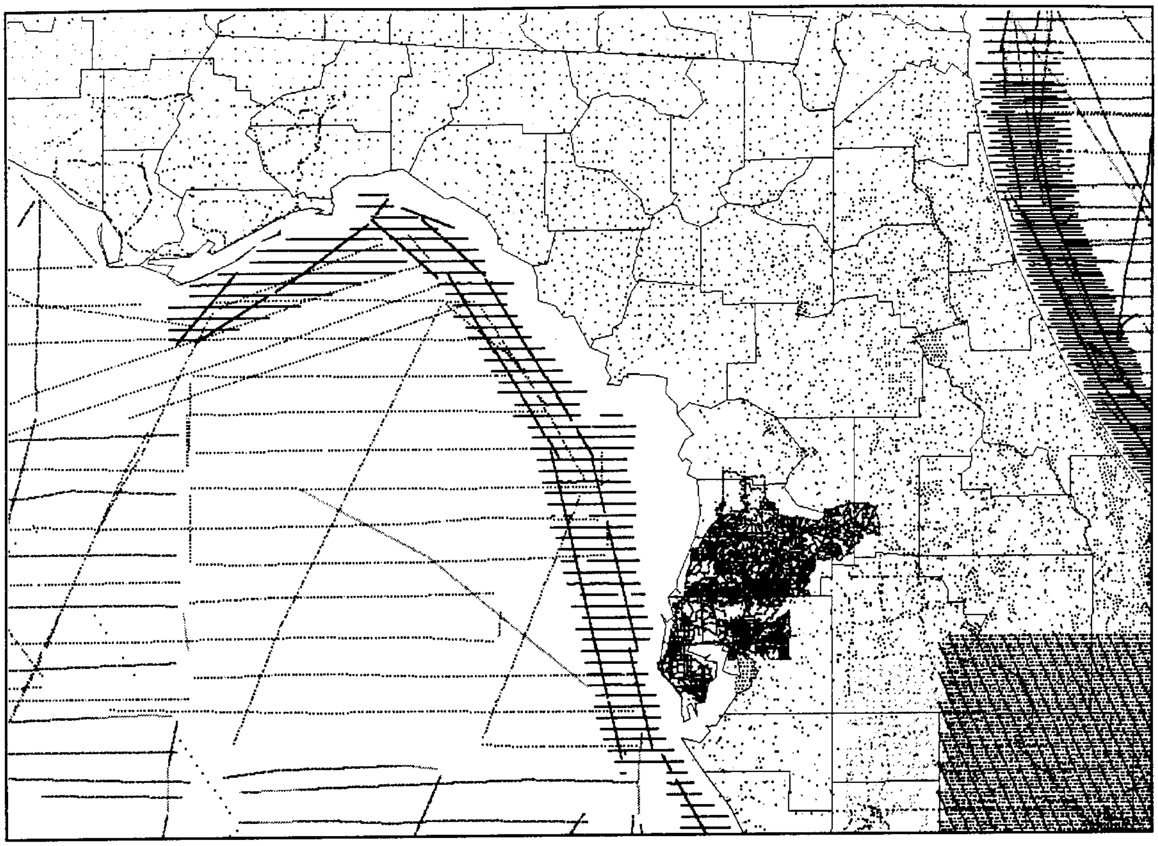

Figure 2a. Area of sparse data coverage.

The area of sparse coverage appears in Figure 2a as the white space off the coast of Taylor, Dixie, Levy, Citrus, Hernando, and Pasco counties. Note the particularly dense terrestrial coverage in Pinellas and Hernando counties. This work completed Milestones 1 and 2 of Phase 2.

3.4 Training of UF Research Associate and Generation of the FLA 98 Geoid Model

During the period June 23 to July 2, 1998, Michael Sartori, a graduate student working toward a PhD in the UF Geomatics Program visited NGS for training on the NGS procedures for generating a geoid model, and to determine what computer software would be needed at UF to enable him to refine the Florida geoid. This training focused on learning the sequence of software programs required to compute a high resolution gravimetric geoid height model. A brief summary of the work accomplished follows.

The two-week period provided an in-depth opportunity for one-on-one training in the suite of software programs developed by NGS that begin with raw gravity measurements and continue through the computation of the geoid undulations. There are well over 100 separate programs, many of them designed to perform a single function or procedure, in the overall process of geoid computation. After becoming familiar with the software and procedures, Mike Sartori worked with Dru Smith to generate the new FLA 98 model. There were four primary differences in the development of FLA98 as compared to GEOID96:

1. A more recent set of gravity anomalies over the oceans, based on an improved set of satellite altimetry data, was used. Gravity anomalies computed in this fashion were available over the Internet. The addition of these data was especially relevant to Florida, given Florida's proximity to the ocean. Figure 2b (FLA98.kms.xyg) is a plot of the area covered by updated altimetry data.

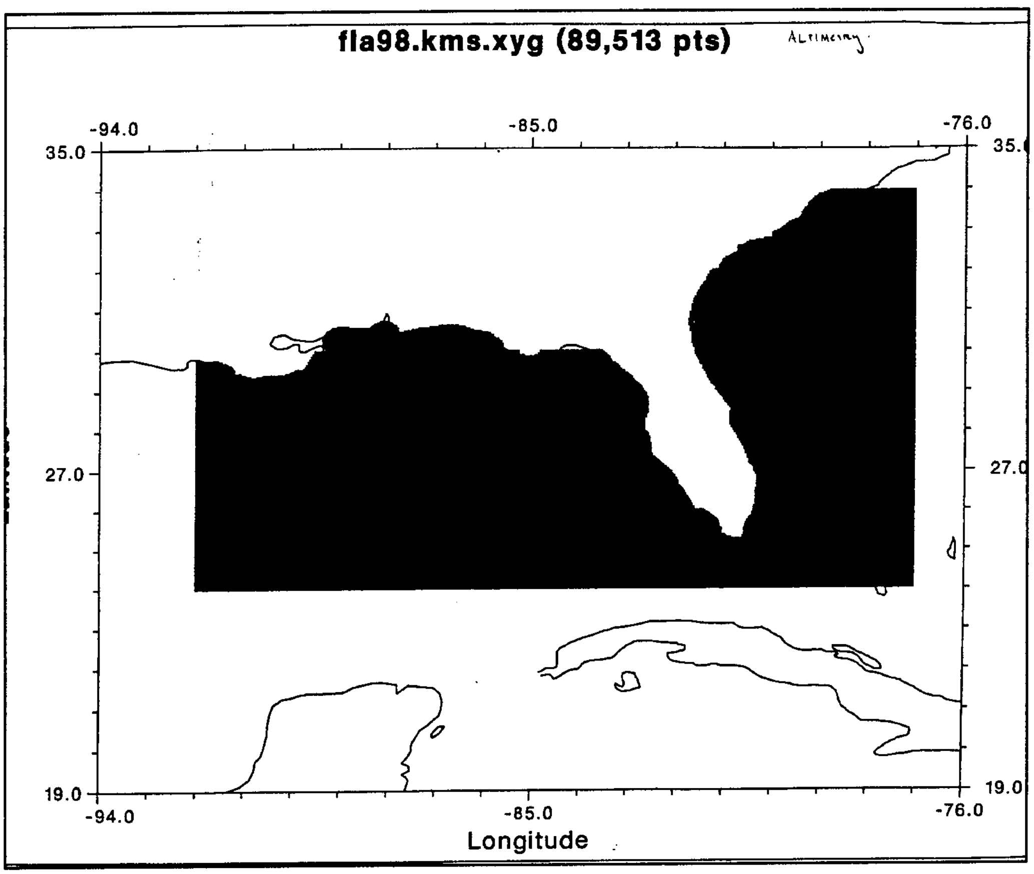

Figure 2b. Plot showing area of satellite altimetry data included in FLA98.

2. New Airborne gravity data, acquired from NIMA, over the Bahamas as well as over a large area of southeast Florida, were included. These airborne data were not available and were therefore not included in the computation of GEOID96. Figure 3 is a plot of the area containing these new airborne gravity measurements; they appear as the dense coverage area over the Bahamas, along the space coast and extending inland into a trapezoidal area over Okeechobee and St. Lucie counties (between 27 and 28 degrees N latitude and 80 and 82 degrees W longitude).

Figure 3. Plot of Area with New Airborne Gravity Data.

3. During the computation of GEOID96, some gravity data in southwest Florida were omitted because of some non-conformity issues. During the subsequent computation of CARIB97 (Caribbean geoid height model) it was later discovered by Dru. Smith and Bob Moose that these terrestrial gravity points in

all likelihood had been mis-coded as ship points. These data were used in the CARIB97 geoid height model, and also in the FLA98 model.

4. GEOID96 was computed on a 2' x 2' grid. The grid size is mostly a function of density of gravity coverage, and must be constant for the entire area to be modeled. FLA98 was computed on a 1' x 1' grid spacing.

3.5 Conclusions and Recommendations

The UF research supported by FDOT resulted in several major achievements:

1. The UF obtained the software, gravity data base, and experience required to develop a regional geoid model.

2. Potential improvements to GEOID96 were identified and NGS will incorporate them into the next generation national geoid model. Until the next generation geoid model is published the FLA98 is available and can be used to check areas where potential problems in GEOID96 are identified. Appendix A contains a copy of a manuscript, submitted for publication, which details the findings of the joint UF-NGS cooperative work.

3. A significant gap in the gravity coverage was identified along the Gulf Coast, north of Clearwater, extending nearly to Panama City. Opportunities should be sought to improve the coverage in this area.

4. The accuracy of the HARN network in Florida is not adequate to reliably remove local deformations from the geoid model, nor to support the determination of orthometric heights to 2 or 5 cm. The new GPS positions of the HARN stations, based on 1999 observations, should be investigated to

determine if they are sufficiently accurate to improve the geoid model and to support GPS orthometric height determinations. The UF could do such a study, but that would require additional funding.

5. The network of CORS stations being developed by FDOT will ultimately provide the high accuracy GPS stations to test and control the regional geoid model, and to serve as base stations for high accuracy measurement of ellipsoid heights with GPS, for conversion to orthometric heights. FDOT should move as quickly as possible to complete the Florida CORS network.

6. NGS does not plan to publish a separate Florida geoid model. The improvements identified in this joint project will be incorporated into the next national model, expected to be completed in 1999 or 2000.

4.0 TEST OF GPS GUIDELINES

4.1 Introduction

In December of 1998 the "Guidelines for Establishing Ellipsoid Heights Using the Global Positioning System" (Carter and Shrestha, 1998), Appendix B, were tested in order to determine if by following the suggested field and office procedures the stated vertical accuracies of 2 cm and 5 cm would be met.

The site of the test area was in South Florida Water Management District Conservation Area 2A, just west of Coral Springs, Florida. GPS observations were collected and processed in accordance with the proposed guidelines to yield ellipsoid heights in the ITRF96. These heights were then transformed to NAD83 ellipsoid heights. Orthometric heights (NAVD88) were calculated by applying geoid heights from 3 different geoid models. These GPS-based orthometric heights were then compared to first-order level-based heights.

4.2 Equipment

Three ASHTECH dual frequency Z-12 geodetic quality receivers were used, along with 3 ASHTECH 700936D choke ring antennas (with radomes). Two-meter Chicago Steel Tape fixed height tripods were used for all sessions.

4.3 Stations

A total of nine stations were occupied. They appear below in Table 5.

Table 5. Project Stations. Vertical datum NAVD88 (Meters).

Project Station	Name	PID	Geoid Height	Published Orthometric Height	Control Orthometric Height
2	C 467	AE7229	-25.118	5.609	5.628
3	FLGPS 69	AD7903	-25.002	5.790	5.799
4	FCE 2079	AD8128	-24.900	4.753	4.753*
5	V 463	AE7217	-25.170	5.986	6.002
6	OTTER	AD7441	-25.317	4.106	4.118
8	G 410 X	AD8121	-24.922	3.550	3.550*
9	FCE 3929	AE7174	-24.998	5.325	5.327
10	H 467	AE7192	-25.243	3.582	3.589
13	D 410 X	AD8116	-24.920	3.771	3.771

* not included in the level loop.

Project station numbers, names, and PID's appear in column 1 - 3. Column 4 contains the geoid height as computed by GEOID96 (NGS). Published orthometric heights (column 5) are as they currently appear on the NGS data sheet. Control orthometric heights (column 6) originate from L25865, a first-order leveling project done by BSM and submitted to NGS. These (column 6) values were accepted as the level-based elevations for comparison to the GPS-derived elevations in the height analysis. Stations 4 and 8 are NOT found in the level loop and are marked with an asterisk. The published orthometric heights were used as the level-based heights for these two stations in the analysis.

4.4 GPS Observations

In accordance with the proposed guidelines, station 4 was chosen to be a Project Control Station (PCS). The closest CORS station is the ATLANTIC OCEANOGRAPHIC & METEOROLOGICAL LABORATORY (AOML) located in Miami, approximately 75 kilometers distant. Station 4 was occupied continuously for a total of 30 hours: 8 hours on day 355, and 22 hours on day 356. During this continuous occupation at station 4, the remaining 8 stations were occupied in 7 sessions of 90 minutes each. Table 6 (below) summarizes the occupation schedule.

Table 6. Session Summary.

Session	**Start Time**	**End Time**	**Time Span**	**Stations**
355 356	15:40 (355)	21:44 (356)	30:04	AOML, 4
355s1	16:24	18:53	2:29	4, 5, 10
355s2	19:11	20:45	1:34	4, 2, 9
355s3	21:01	22:43	1:42	4, 3, 13
356s1	13:40	15:30	1:50	4, 6, 8
356s2	15:52	17:25	1:33	4, 5, 13
356s3	17:46	19:26	1:40	4, 2, 10
356s4	19:42	21:25	1:43	4, 3, 9

In column one, 355 and 356 refer to the day of year on which the observation took place. The times recorded in columns two and three are GMT, 5 hours ahead of local time. Three sessions involving 6 stations took place on day 355; 4 sessions involving all 8 stations took place on day 356. Six stations (2, 3, 5, 9, 10, and 13) were occupied twice (once on each day), while two stations (6 and 8) were occupied with only a single 90-minute session on day 356. No station had any significant obstructions, and all satellites above 10 degrees were tracked. VDOP remained below 3.0 at all times.

4.5 Processing and Analysis of PCS 4

The thirty hours of observations at station 4 and the CORS AOML were divided into 4 sessions of approximately 7.5 hours each, and were processed with the PAGES (WinNT) program. (Note: PAGES software is available from NOAA). Tropospheric parameters were solved. Results appear below in Table 7.

Table 7. PCS Session Agreement at Hub Station 4.

Session	**Station 4 h**	**Session RMS**	**Delta X**	**Delta Y**	**Delta Z**	**Length**	**Local Start Time**	**Local End Time**
355a	-21.82	0.01	41881.38	-22535.12	-59802.12	76407.95	0.44	0.79
356a	-21.80	0.01	41881.38	-22535.10	-59802.12	76407.95	0.79	0.08
356b	-21.81	0.01	41881.37	-22535.11	-59802.12	76407.95	0.08	0.38
356c	-21.78	0.02	41881.37	-22535.08	-59802.13	76407.94	0.38	0.70

The difference between the highest ellipsoid height value (-21.7806, session 356c) and the lowest value (-21.8195, session 355a) is 3.89 cm. It is significant that the height component for these two 7.5 hour sessions disagree by nearly 4 cm. A possible explanation lies in the fact that these are the two daytime sessions; the two night sessions agree to within 4.1 mm. Local tropospheric differences occurring in daytime hours over the 76 kilometer baseline may have contributed to this lack of precision.

4.6 Processing and Analysis of Spur Sessions

Following the processing of the four "hub" sessions, the seven 90-minute "spur" sessions were processed holding the calculated session ellipsoid height at station 4. This means that the hub station ellipsoid height was constrained to the value obtained during the particular 7.5-hour period during which the spur sessions were actually observed (the daytime sessions). This was done in order to account for the time-dependent variation in the ellipsoid height at station 4. Tropospheric parameters were NOT solved. Table 8 summarizes the baseline results. Values are in units as noted.

Table 8. Spur Session Agreement.

Station	ITRF96 h (M)	Spread (mm)	Session	Session RMS (cm)	BL (Km)	Receivers #
2	-21.160 -21.161	**1**	355s2 356s3	2.3 2.0	17.3	3r 3r
3	-20.870 -20.860	**10**	355s3 356s4	1.5 1.0	8.8	2r 2r
5	-20.844 -20.856	**13**	355s1 356s2	1.7 2.0	17.2	3r 3r
6	-22.864	**1 observation**	356s1	1.7	24.0	3r
8	-23.010	**1 observation**	356s1	1.7	11.0	3r
9	-21.302 -21.308	**6**	355s2 356s4	2.3 1.0	18.2	3r 3r
10	-23.250 -23.310	***60***	355s1 356s3	1.7 2.0	26.6	3r 3r
13	-22.800 -22.814	**17**	356s2 355s3	2.0 1.5	18.2	3r 3r

Note that of the six stations that were observed on both days, all but one (station 10) had agreement better than 17 mm. This is well within the proposed specification that calls for the spread between measurements to be less than 30 mm. Station 3 was processed in 2-receiver sessions because results obtained in 3-receiver processing showed irregularities that didn't appear when reprocessed in two 2-receiver sessions. Trying this technique with station 10 failed to improve results.

4.7 Orthometric Heights

The ITRF96 coordinates obtained on the spur stations from session processing were then translated and rotated into the NAD83 reference frame using the 7-parameter transformation program TRANSF.EXE written by NGS (note:TRANSF.EXE by NOAA is free and available on the web). Using the geoid height (N) computed from GEOID96 and the ellipsoid height (h), an orthometric height (H) was calculated for all stations relative to station 4 by the equation H = h - N. Orthometric heights calculated in this manner were then compared with the elevations obtained by leveling. Results are summarized in Table 9. All values are in meters.

Table 9. Orthometric Height Comparison. (NAVD88 Datum GEOID96).

Station	ITRF96 h	transf	Geoid height GEOID96	GPS H	Level H	GPS - Level	Bias Remvd Final Diff
2	-21.160	1.620	-25.118	5.578	5.628	**-0.050**	**-0.019**
2	-21.161	1.620	-25.118	5.577	5.628	**-0.051**	**-0.020**
3	-20.870	1.621	-25.002	5.753	5.799	**-0.046**	**-0.015**
3	-20.860	1.621	-25.002	5.763	5.799	**-0.036**	**-0.005**
5	-20.844	1.623	-25.170	5.949	6.002	**-0.053**	**-0.022***
5	-20.856	1.623	-25.170	5.937	6.002	**-0.066**	**-0.035***
6	-22.864	1.624	-25.317	4.078	4.118	**-0.040**	**-0.010**
8	-23.010	1.625	-24.922	3.537	3.550	**-0.013**	**0.017**
9	-21.302	1.626	-24.998	5.322	5.327	**-0.005**	**0.026***
9	-21.309	1.626	-24.998	5.316	5.327	**-0.011**	**0.020***
10	-23.250	1.627	-25.243	3.620	3.589	**0.031**	**0.062***
10	-23.310	1.627	-25.243	3.560	3.589	**-0.029**	**0.002***
13	-22.797	1.627	-24.920	3.749	3.771	**-0.022**	**0.009**
13	-22.814	1.627	-24.920	3.732	3.771	**-0.039**	**-0.008**
						Local Bias = 0.031 **Bias =0.031**	

Column two contains the GPS-derived ellipsoid heights in the ITRF96 as derived by PAGES. Column three is the translation value computed by TRANSF. Column four contains the geoid heights as computed by GEOID96. Column five is simply H = h - N. Column six contains the elevations determined by leveling. Column seven contains the GPS-derived orthometric height minus the leveled elevation. The local bias present in GEOID96 is taken to be the mean of the differences between the GPS derived elevations and elevations based on leveling, calculated to be 0.0307. The last column contains the final difference between GPS-derived values and the level-derived values with the calculated local bias of GEOID96 removed. Stations where the differences between GPS and level-derived heights were greater than 2 cm are marked with an asterisk. A final comparison is presented in Table 10.

Table 10. Differences Between GPS and Level-derived Heights.

Station	Number of Measurements	Average Final Difference between GPS-derived height and Level-derived height
2	2	19.5 mm
3	2	-10.0 mm
5	2	-28.5 mm
6	1	-10.0 mm
8	1	17.0 mm
9	2	23.0 mm
10	2	32.0 mm
13	2	0.5 mm

Five stations (2, 3, 6, 8, and 13) had a GPS derived elevation which matched the level-derived elevation at or better than 2 cm.

4.8 Geoid Models

To determine if a particular geoid model had a significant effect on the precision with which the GPS-derived elevations agreed with the level-derived values within the project area, orthometric heights were computed using the ellipsoid heights measured in the previous section by using 3 geoid models:

GEOID96 (NGS). This model incorporates a "correction" surface generated from GPS-benchmark data that much improves the fit between NAVD88 orthometric heights and GPS measured ellipsoid heights. This is the model used in the previous analysis.

G96SSS (NGS). This model is a pure gravimetric geoid model, with no correction surface. It has a larger systematic offset, but is not influenced by benchmark data.

FLA98 (NGS and UF) is also a pure gravimetric geoid model. This experimental geoid model is a product of the collaboration between NGS and UF; it incorporates more recent satellite altimetry, corrected mis-coded gravity values in southwest Florida, and added airborne gravity not available in GEOID96.

The ITRF96 coordinates obtained on all stations from PAGES session processing were again translated and rotated into the NAD83 reference frame using the 7-parameter transformation program TRANSF.EXE written by NGS. Using the geoid height computed from the 3 geoid models, 3 different orthometric heights (H) were calculated by the equation

$H = h - N$. These results are presented in Table 11.

Table 11. Height Comparison using different geoid models.

Sta	ITRF96 h	Level H	N (GEOID96)	NAD83 GPS H	Bias Rmvd Geoid96 M - C	N G96SSS	NAD83 GPS H	Bias Rmvd		NAD83 GPS H	Bias Rmvd FLA98A M - C
								G96SSS M - C	N FLA98A		
2	-21.16	5.628	-25.118	5.578	-0.019	-26.260	5.100	-0.029	-26.944	5.784	-0.027
2	-21.161	5.628	-25.118	5.577	-0.020	-26.260	5.099	-0.029	-26.944	5.783	-0.028
3	-20.870	5.799	-25.002	5.753	-0.015	-26.151	5.281	-0.019	-26.832	5.962	-0.020
3	-20.860	5.799	-25.002	5.763	-0.005	-26.151	5.291	-0.009	-26.832	5.972	-0.010
4	-21.802	4.753	-24.9	4.72	-0.002	-26.050	4.248	-0.006	-26.736	4.934	-0.002
5	-20.844	6.002	-25.170	5.949	-0.022	-26.317	5.473	-0.029	-27.002	6.158	-0.027
5	-20.856	6.002	-25.170	5.937	-0.035	-26.317	5.461	-0.042	-27.002	6.146	-0.040
6	-22.864	4.118	-25.317	4.078	-0.01	-26.462	3.599	-0.020	-27.151	4.288	-0.014
8	-23.010	3.550	-24.922	3.537	0.017	-26.088	3.078	0.027	-26.765	3.755	0.021
9	-21.302	5.327	-24.998	5.322	0.026	-26.165	4.863	0.035	-26.844	5.542	0.032
9	-21.309	5.327	-24.998	5.316	0.02	-26.165	4.857	0.029	-26.844	5.536	0.025
10	-23.250	3.589	-25.243	3.620	0.062	-26.402	3.152	0.062	-27.088	3.838	0.066
10	-23.310	3.589	-25.243	3.560	0.002	-26.402	3.092	0.002	-27.088	3.778	0.006
13	-22.797	3.771	-24.920	3.749	0.009	-26.092	3.295	0.023	-26.769	3.972	0.017
13	-22.814	3.771	-24.920	3.732	-0.008	-26.092	3.278	0.006	-26.769	3.955	0.001

A comparison of the three geoid models is summed in Table 12.

Table 12. Summary of geoid model comparison.

Model	Bias (M)	RMS (M)
GEOID96	0.031	0.024
G96SSS	0.499	0.030
FLA98A	-0.183	0.028

Of the three geoid models, Geoid96 performed best in the project area. Not only is the absolute value of the local bias the smallest (as expected), the average differences between measured and control values, standard deviation, minimum difference, and maximum difference all out-performed the pure gravimetric geoid models.

4.9 Conclusions

Field and office work was performed on a test project area in South Florida for the purpose of determining that if the guidelines proposed in "Guidelines for Establishing Ellipsoid Heights Using the Global Positioning System" (Carter, Shrestha, 1998) were followed, then prescribed accuracy levels in GPS-derived heights could be obtained.

In general it appears that the guidelines are adequate for obtaining the prescribed accuracy in GPS-derived heights. This study (although admittedly based on limited observations) found that in 5 out of 6 cases, the height component of two 90-minute sessions agreed better than the called-for 3 cm spread. Perhaps less significant but still noteworthy (because of the unknown amount of allowable misclosure, and/or compensating errors in the first-order level loop L25865), in 5 out of 8 cases GPS-derived elevations agreed with level-derived elevations better than 2 cm.

It was troublesome to note that the repeatability of the height component of the four 7.5 hour sessions to the CORS station (76 kilometers distant) was not better that the 3.9 cm mentioned above.

Finally, in this local project area GEOID96 (NOAA) did an adequate job of modeling the geoid heights. Although an extremely flat area topographically, the geoid slope is significant, sloping over 30 cm in 25 kilometers (12 ppm).

APPENDIX A

Preliminary investigations toward an improved geoid model in Florida

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Abstract

A joint study between the National Geodetic Survey and the University of Florida was performed which investigated the possibility of improving the geoid model in Florida. Since the computation of G96SSS and GEOID96, new gravity data have been made available to NGS, including airborne surveys over Florida and the Bahamas, as well as updated satellite altimetry-derived gravity anomalies. Additionally, offshore gravity data found to be erroneous in the G96SSS and GEOID96 computations have been identified and corrected. This study has attempted to identify how such changes might improve the knowledge of the geoid in Florida.

Two experimental geoids FLA98A and FLA98B were computed, incorporating these changes in different ways. The geoids were computed on 1' x 1' grid spacings, covering the area of 24° to 33° N, 269° to 282° E. The initial results indicate that the Florida airborne data does not improve, and may actually degrade, the geoid solution. Introduction of the new altimetry, fixing the erroneous offshore data, adding the Bahamas airborne data, and removal of gravity value outliers do result in changes in the geoid model of a few to several centimeters in local areas. Computation of geoid models in small areas (such as the state of Florida) are more prone to biases and tilts, so a state-wide comparison of the FLA98A and FLA98B models to GEOID96 is difficult. However, in many localized areas the FLA98A and FLA98B models showed some areas of improvement over GEOID96, predominantly from fixing errors in the local gravity

measurements. There were, however, some local degradations in these models as well, mostly from the addition of questionable airborne gravity data.

1. Introduction

In October 1996, NGS computed G96SSS and GEOID96, high resolution geoid models for the United States (Smith and Milbert, 1999). G96SSS was a purely gravimetric, geocentric geoid model, based on gravity measurements held by NGS as well as evaluated, releasable gravity held by the National Imagery and Mapping Agency (NIMA). GEOID96 was computed by adding a smooth conversion surface, computed from GPS derived NAD 83 ellipsoid heights on NAVD 88 leveled benchmarks, to G96SSS. Both geoid models were produced on a 2' x 2' grid, and used the best available geoid computational theory. The absolute agreement between GEOID96, NAD 83 GPS derived ellipsoid heights and NAVD 88 leveled Helmert orthometric heights at 2951 benchmarks around the conterminous United States is +/- 5.5 cm RMS (1 sigma), with a co-variance of $(2.5)^2$ cm^2 for benchmarks separated by 5 km, decorrelating around 25 km. In Florida, although there are somewhat poorer quality GPS derived ellipsoid heights, those statistics are identical to the nationwide statistics.

In 1997 the Florida Department of Transportation (FDOT) and the Florida Department of Environmental Protection (FDEP) approved University of Florida (UF) research proposals to explore improving the determination of orthometric heights using the Global Positioning System (GPS). The research plan included two major components: 1) to develop and test simplified guidelines for the observation of ellipsoid heights using GPS (Carter and Shrestha, 1998), and 2) to evaluate the precision of GEOID96 over Florida and investigate possible places for improvement. The UF approached the National Geodetic Survey (NGS) and the two organizations agreed to work cooperatively, with the NGS providing computer software, training for UF personnel, and access to the NGS gravity data base. The National Imagery and Mapping Agency (NIMA) also agreed to make certain data available from their gravity data base. This paper represents the results of that joint study.

Section 2 discusses those places where potential geoid improvements, specific to Florida, might occur. Section 3 discusses the first experimental geoid, while section 4 contains more detailed discussion about the inclusion of airborne data. Detailed comparisons of the various geoid models against GPS on leveled benchmarks are made in section 5, and conclusions are drawn in section 6.

2. Places for potential improvement of the Florida geoid model

It was postulated at the beginning of this study that future improvements to the Florida geoid model will derive from a variety of activities including: improved editing of the gravity data base to identify and remove outliers, the inclusion of additional offshore and on-land gravity measurements in the Florida region, the development of new global and continental scale geoid models, and improvements in GPS-derived heights in Florida. This paper focuses on the NGS-UF work to improve the gravimetric geoid model and, as one component of this process, evaluating the need for additional gravity data in the Florida region.

There were obvious places where the gravimetric geoid might be improved. For example, a 12.3 cm bias occurred in G96SSS due to the adoption of an incorrect "best fitting ellipsoid to mean sea level." However, this error was corrected in GEOID96, and does not affect the determination of orthometric heights with GPS. Also in G96SSS, satellite altimeter derived gravity anomalies computed by Sandwell and Smith (1997) were used. Some tests performed at NGS (Smith, 1997) indicate that more recent data, computed at Denmark's Kort og Matrikelstyrelsen (KMS) might yield long-wavelength improvements to terrestrial geoid models. Satellite altimeter measurements, due to inadequacies in shallow water tide models (Shum et al, 1997), are generally unreliable in water depths of less than 500 m. As such, altimeter derived gravity anomalies are used far from land, and it was recognized that changing such a distant data set would add biases, tilts and long wavelength changes to the terrestrial geoid model (Smith, 1997), but would have virtually no effect on geoid features over distances of tens of kilometers.

There were other areas to consider as well. After NGS released G96SSS and GEOID96 it was discovered that a few thousand gravity points in the shallow waters off the southwest coast of Florida were incorrectly labeled as "land" gravity. This caused an erroneous tilt in G96SSS. However, most of that tilt was removed from GEOID96, by inclusion of GPS-derived ellipsoid heights on leveled benchmarks. In addition, NGS and UF had access to NIMA's unevaluated helicopter-borne gravity surveys over the east coast of Florida and the Bahamas, which had not been used in G96SSS.

From a computational standpoint, one might argue that a finer grid spacing could improve one's knowledge of the geoid. If the geoid is computed on a 1' x 1' grid, interpolation error from that grid is reduced to the sub-centimeter level, but one must have gravity data with adequate spacing to support a 1' x 1' grid. In the Florida area, terrestrial 6' x 6' gravity coverage is over 90%, but that number quickly drops below 50% for 2' x 2' (and finer) coverage. Even so, it was decided to use a 1' x 1' grid for computing the experimental Florida geoid models.

One definite, yet labor intensive, method to improve a geoid model is to increase the reliability of available data. That requires investigating the gravity databases for outliers, and could include performing geophysical forward modeling to anticipate the magnitude of gravity changes in an area. A large portion of the available gravity in Florida (and the U.S.A., in general) had been evaluated by NIMA, and made available to NGS, but the NGS database had not been studied so exhaustively, and the potential for local outliers remained. Due to the time involved in such an undertaking, this was not done in a comprehensive way for this study. However, data editing remains a task of serious importance if one wishes to improve the geoid in very local areas.

Finally, it must be pointed out that the ability to evaluate a geoid model is strongly dependent on good GPS heights at benchmarks with good leveled heights. The GPS height data in Florida, used in GEOID96 were from the 1991 observation campaign for the development of the Florida High Accuracy Reference Network (HARN). New GPS processing information, such as the use of antennae phase centers (Schupler et al, 1991; Wübbena et al, 1997), and new guidelines for achieving 2 cm heights (Zilkoski et al, 1997) have arisen since 1991. These changes in the collection and processing of GPS data yield more reliable ellipsoid heights, which are equally important in deriving orthometric heights with GPS.

3. First experimental geoid

This study was begun by computing an experimental geoid, designated FLA98A. This model was computed using the remove-compute-restore procedure, like G96SSS (Smith and Milbert, 1999), with EGM96 (Lemoine et al, 1997) as a reference field. Unless noted below, the entire procedure follows that for computing G96SSS.

The FLA98A geoid model was computed using an approximation to the Helmert second method of condensation. This leaves the geoid model susceptible to theoretical errors, especially in the realm of computing terrain corrections and downward continuing gravity data to the geoid. Florida, generally having both flat and low terrain, will be minimally impacted by these theoretical drawbacks, at least for data taken at the Earth's surface. However, airborne gravity, which was used in FLA98A, was collected between 500 and 2000 meters above sea level, and may introduce errors in the downward continuation process.

The 12.3 cm bias of G96SSS was corrected by adopting W_0 (potential on the geoid) as 62636856.88 m^2/s^2 (Burša, 1995). The erroneously coded gravity data on the southwest coast of Florida were fixed, and the two airborne gravity surveys were included in the input gravity set. Figure 1 shows the location of existing gravity coverage (aside from satellite altimetry) in the Southeast Florida region. Figure 2 shows the location of the new airborne gravity points added. Note that the new data are especially critical around the Bahamas region.

New satellite altimeter derived gravity anomalies were used, from KMS (Knudsen and Andersen, 1998, personal communication). Tests by R. Rapp at the Ohio State University

(1998, personal communication) indicate that these data are in better agreement with ship gravity than either the Sandwell and Smith (1997) anomalies, or the older KMS anomalies (Knudsen and Andersen, 1997). These data were only used in FLA98A if they occurred at least 50 km from shore, and in water over 200 m deep (due to inaccuracies in existing shallow water tide models).

Because UF was interested in the Florida area exclusively, the computational area was chosen to be 24° to 33° N, 269° to 282° E. Of course, like any local geoid computation in a small area, it was expected that this geoid model would have some bias (and tilt) induced by working in a small area. Finally, the grid spacing was chosen to be 1' x 1', primarily because computational resources allowed, though it was known that few areas of Florida actually have data at that spacing and finer.

FLA98A was computed using a spherical 1-D FFT application of the Stokes' integral (see Smith and Milbert (1999) for more details). Including the altimetry and airborne gravity, there were 425,057 gravity points used in this computation.

3.1 FLA98A vs. G96SSS

In order to compare these two geoid models, G96SSS was biquadratically interpolated onto a 1' x 1' grid, and FLA98A was subtracted from it. The differences are plotted in Figure 3. These differences range from -10 cm to +221 cm. Note that the largest differences are in the oceans (as expected). However, there are some local, high frequency changes (some of them being "improvements", others not) to the terrestrial geoid model.

The first is clearly the central east coast where the dense airborne survey was added, yielding local changes of 64 to 72 cm (though much of that is a bias and tilt introduced by new altimetry data and using a different computational area than G96SSS). The second is along the west coast where gravity data gaps occur. These west coast changes in the geoid are due to slight variations that occurred as the gravity was interpolated across data gaps. Because these changes in the geoid are not due to any new information, the changes are considered unreliable. If actual gravity measurements become available for these data gaps, they should be thoroughly examined for their ability to improve the geoid model. The data coverage, and a clearer picture of the size of these data gaps can be seen in Figure 4. Note that altimetry can not be used to fill in this near-shore gravity gap, as the continental shelf off the west coast of Florida extends 200 km offshore, rarely deeper than 50 meters. To improve the geoid in these areas clearly requires additional gravity measurements in these gaps. A brief investigation of the Bouguer anomalies in this area indicates that a -15 mgal linear feature extends from the terrestrial gravity data to the offshore ship gravity data. This feature is briefly "lost" in the data gap because the interpolation software is incapable of replicating the feature without gravity measurements in that gap. Loss of a 15 mgal feature over such a large area can impact the geoid by a few cm in surrounding areas (including the terrestrial near shore areas), and therefore an argument can be made for collecting additional data in these gaps.

Note that in all other terrestrial areas, the only changes are very long wavelength ones. However, these long wavelength changes are not entirely insignificant. Although the Florida geoid is generally smooth, the local ecosystems are extremely prone to small tilts in the geoid. Water flow and subsequent biological changes can be sensitive to geoid tilts as small as 1 cm over tens of kilometers [Bill Carter, University of Florida, 1999, personal communication; Raabe et al, 1996].

3.2 Test of FLA98A vs. GPS/Benchmarks

As with G96SSS (Smith and Milbert, 1999), a comparison was made between FLA98A and GPS derived ellipsoid heights (in the ITRF94 frame, relative to the GRS-80 ellipsoid) on benchmarks with leveled NAVD 88 Helmert orthometric heights. Table 1 summarizes the initial findings.

Table 1: GPS/BM residuals for the whole area		
	G96SSS	FLA98A
# of Benchmarks	543	543
Average (N+H-h)	50.8 cm	-10.4 cm
Standard Deviation	+/- 10.6 cm	+/- 12.0 cm
Minimum (average removed)	-48.8 cm	-47.0 cm
Maximum (average removed)	+24.8 cm	+35.6 cm

The average residual is of little interest. The averages must be different because of the 12.3 cm bias in G96SSS, and the choice of two different computational areas, as well as the large scale changes of using different altimetry. It is interesting to see an increase in the standard deviation in the FLA98A residuals. This is most likely due to the long wavelength tilts between G96SSS and FLA98A. In order to gauge high frequency changes, a tilt is removed from both sets of residuals and statistics are generated again. This is shown in Table 2.

Table 2: Detrended GPS/BM residuals for the whole area		
	G96SSS	FLA98A
# of Benchmarks	543	543
Azimuth of trend removed	355°	19°
Size of trend removed	0.29 ppm	0.33 ppm
Standard Deviation	+/- 9.0 cm	+/- 8.6 cm
Minimum	-36.5 cm	-30.2 cm
Maximum	+25.5 cm	+33.3 cm

Table 2 shows that there is a small difference between the detrended residuals of G96SSS and FLA98A. That is, if one disregards the long wavelength biases and tilts between the models, one may make the argument that a slight improvement is seen with FLA98A. The changes specifically in the area of the airborne data should give an indication of how those data are affecting the geoid locally.

4. Florida Airborne data

The most significant high-frequency changes expected between FLA98A and G96SSS are from the incorporation of airborne data directly over Florida. Since FLA98A incorporated many changes from G96SSS, it is useful to know how much of the difference between FLA98A and G96SSS is due only to this airborne data over Florida. As such, a second experimental geoid, FLA98B, was computed. FLA98B was computed with exactly the same data and procedures as FLA98A except the airborne gravity data was not included over Florida. The difference between FLA98A and FLA98B is very localized. The differences between the two geoids, just in the area of the airborne data are given in Table 3.

Table 3: Statistics of FLA98B minus FLA98A in the region (27° to 28° N, 278.5° to 280° E)	
Average	+1.1 cm
Standard Deviation	+/- 1.2 cm
Minimum	-1.8 cm
Maximum	+4.8 cm

To gain an understanding of how the airborne gravity improves or degrades the geoid, the geoid models were compared to the GPS/Benchmark data just in the area of 27° to 28° N, 278.5° to 280° E. The results are in Table 4.

Table 4: Detrended GPS/BM residuals for the airborne gravity area			
	G96SSS	FLA98A (with airborne)	FLA98B (no airborne)
# of Benchmarks	57	57	57
Azimuth of trend removed	33°	354°	7°
Size of trend removed	0.38 ppm	0.60 ppm	0.70 ppm
Standard Deviation	3.1 cm	3.6 cm	3.2 cm
Minimum	-8.8 cm	-9.1 cm	-10.5 cm
Maximum	+8.1 cm	+8.7 cm	+8.3 cm

As seen in Table 4, the statistics show a slightly worse performance for both of the FLA98 geoid models, relative to that of G96SSS. Because biases and tilts have been removed, it is concluded that no useful high frequency information is actually gained in using the airborne data. In fact, the somewhat higher standard deviation for FLA98A seems to imply that small, local, high frequency degradations of the geoid model are occurring. Whether that is due to noisy airborne gravity data, or errors in downward continuation of the airborne gravity are not clear.

5. Comparison with GPS on Benchmarks

In order to get a broad perspective on the properties of the two different geoid models, a test is made by accumulating the statistics of misclosures between geoid models and GPS on benchmarks when organized into 1° x 1° cells. Table 5 shows these results. Note that Table 5 only displays statistics for those cells that have 7 or more GPS benchmarks, in order to provide more robust estimates. The columns of latitude and East longitude refer to the southwest corner of a given 1 degree cell, number indicates the number of GPS benchmarks within that cell. Average shows the average misclosure for a given geoid model, and RMS gives the root mean square about that average for the given geoid model and 1 degree cell. The Diff columns show the algebraic differences between the geoid model statistics for both the cell averages and the cell RMS's.

Table 5: Misclosures between GPS/BM/geoid models sorted into 1°x 1° areas								
Lat.	Long.	Number	Average (G96SSS)	Average (FLA98A)	Diff.	RMS (G96SSS)	RMS (FLA98A)	Diff.
24°	278°	17	-31.29	-24.50	-6.79	7.48	8.49	-1.01
25°	279°	21	-11.06	-9.33	-1.73	8.82	5.36	3.46
26°	278°	20	-3.25	-3.63	0.38	4.48	4.10	0.38
26°	279°	25	0.48	-4.10	4.58	5.71	5.21	0.50
27°	277°	58	-3.75	-4.03	0.28	4.92	4.83	0.09
27°	278°	7	2.37	0.72	1.65	5.28	5.57	-0.29
27°	279°	38	3.34	-1.00	4.34	3.80	4.09	-0.29
28°	277°	8	11.97	11.26	0.71	3.54	3.77	-0.22
28°	278°	45	2.45	2.67	-0.21	3.31	3.32	-0.01
28°	279°	23	4.58	5.33	-0.75	3.47	3.77	-0.30
29°	278°	14	10.87	12.78	-1.92	6.99	7.34	-0.35
30°	272°	7	-0.84	-1.28	0.43	4.57	3.81	0.75
30°	273°	22	0.55	-0.15	0.70	6.90	6.40	0.49
30°	274°	8	5.99	3.59	2.40	6.84	5.96	0.88
30°	276°	7	8.73	9.86	-1.13	6.70	7.36	-0.65
30°	278°	17	16.23	21.45	-5.21	7.33	7.12	0.20

The occurrence of large differences in the cell averages indicate the presence of longer scale, systematic error. Whereas, the differences in cell RMS show small scale, or random errors. In general, positive RMS differences indicate more local error in the G96SSS geoid model, and negative RMS differences show more local error in the FLA98A geoid model. The sign of the difference of the cell averages has no inherent meaning, but the magnitude of the differences of the cell averages does have meaning. A larger average difference, means the geoid models vary significantly from one another.

The largest average difference of -6.79 cm at (24°, 278°) indicates a local improvement in the FLA98A geoid model. The misclosure is generated by the erroneously coded offshore gravity data set that was corrected in the CARIB97 geoid model (Smith and Small, 1999), but which was still present in G96SSS. Of interest, one finds a 1.01 cm increase in the FLA98A RMS. Despite this conflict, it is felt that the FLA98A is locally better in that cell. Note, also, the smaller average difference and larger RMS difference in the cell just to the North (25° , 279°); which is caused by local tilt in the G96SSS model, generated by the problem data to the South.

The RMS decrease of 0.88 cm at cell (30°, 274°) indicates the local effects of a bad gravity point in the G96SSS model that was corrected in the CARIB97 geoid model (ibid). This is a case where local geoid model improvement was found by the GPS on benchmarks. This example illustrates a 2 cm change related, in part, to a cleaner gravity data set used in the FLA98 models.

The offset of +4.34 cm at cell (27°, 279°) is generated by the incorporation of helicopter-borne gravity data. This cell shows a degradation of the cell RMS when including those data. Note that this behavior is also evident in the adjacent cell, (27°, 278°). These results were already highlighted in Table 4.

Some results are not clear. For example the cell at (30°, 278°), which includes Jacksonville, shows a 5 cm cell average difference between the geoid models. It is suspected that the result is related to use of a different satellite altimeter data set in FLA98A. However the small difference in RMS does not provide much guidance on the geoid accuracy. Note that other studies have pointed out the significant GPS ellipsoidal height error in Florida (Milbert, 1998) at the +/- 10 cm level. To some extent, the interpretation of RMS differences may depend on the size of the RMS in a given 1 degree cell, as well as the number of GPS benchmarks, and magnitude of the average misclosure difference.

6. Conclusions and recommendations

Two experimental geoid models, FLA98A and FLA98B were computed on a 1' x 1' grid, covering Florida and surrounding areas. New altimetry-derived gravity anomalies from

Denmark's KMS were used in deep ocean areas. Known biases and erroneous gravity in G96SSS were corrected in both models. The only terrestrial gravity change was the introduction of an airborne gravity data set over the central east coast of Florida.

The experimental geoids, as well as G96SSS, were compared against GPS derived ellipsoid heights on NAVD 88 leveled benchmarks. After biases and trends were removed, it was concluded that inclusion of the airborne gravity may have locally degraded the geoid model, over terrestrial Florida. This conclusion, however, is dependent upon the reliability of the early HARN GPS data, and leveling data, on the east coast of Florida. However, the effects of bad gravity points in G96SSS (identified and corrected in CARIB97) were again identified and corrected in the FLA98 models, and the improvements confirmed through a comparison with GPS on benchmarks, in local areas. Additionally, it was shown that localized geoid noise (such as that induced by the noisy airborne gravity data) can be identified through the use of GPS on benchmarks.

The inclusion of all other gravity data, being offshore, mostly introduces biases, tilts and long wavelength changes in the terrestrial geoid. Changing from a 2' x 2' grid (as per G96SSS) to 1' x 1' does not increase high frequency information due to both the smooth nature of the geoid in Florida, and the general lack of gravity data to support such a spacing. However, as mentioned before, the overall smoothness of the Florida geoid can not de-emphasize the importance of knowing long wavelength geoid tilts to a high accuracy, due to their impact on waterflow and ecology.

While the introduction of new, densely spaced, terrestrial data has the potential to improve the geoid model, data taken at altitude (airborne) may be both too noisy, and too difficult to properly downward continue, to yield enough useful information to improve the geoid. It is concluded, therefore, that additional detailed studies on the use of airborne gravity data be conducted before further data collection of this sort is undertaken.

Lastly, it is noted that the ultimate goal of this research was to improve the accuracy of orthometric heights derived from GPS observations. In order to conclusively state that any geoid model is more accurate than another, there must be reliable GPS and leveling data for testing the geoid models. Re-observations of the Florida GPS network are scheduled for March 1999 (Steve Frakes, NGS and Dave Zilkoski, NGS, personal communication, 1999). Also, the FDOT has initiated a program to develop a network of Continuously Operating Reference Stations (CORS) that will provide coverage of the entire State of Florida at about 50 kilometer spacing, which will greatly improve both the number of very high accuracy stations available for intercomparison with geoid models and facilitate the convenient use of GPS for the determination of accurate ellipsoid heights, and in turn, orthometric heights.

7. Acknowledgments

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Figure Captions:

Figure 1: Existing Terrestrial and Ship Gravity Coverage over Southeast Florida and the near Caribbean

Figure 2: New Airborne Gravity Coverage

Figure 3: Differences between G96SSS and FLA98A (Magenta = 40 cm and lower, Red = 70 cm and higher)

Figure 4: Gravity coverage on the northern West coast of Florida

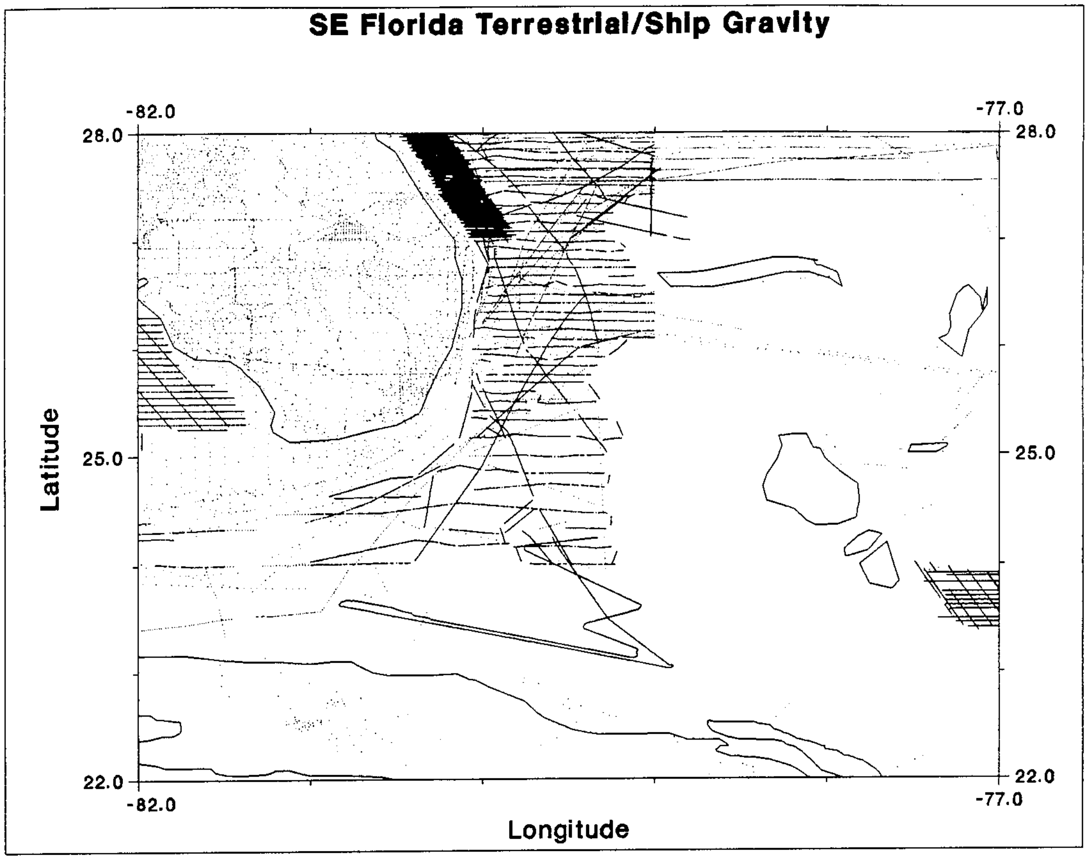

Figure 1: Existing Terrestrial and Ship Gravity Coverage over Southeast Florida and the near Caribbean

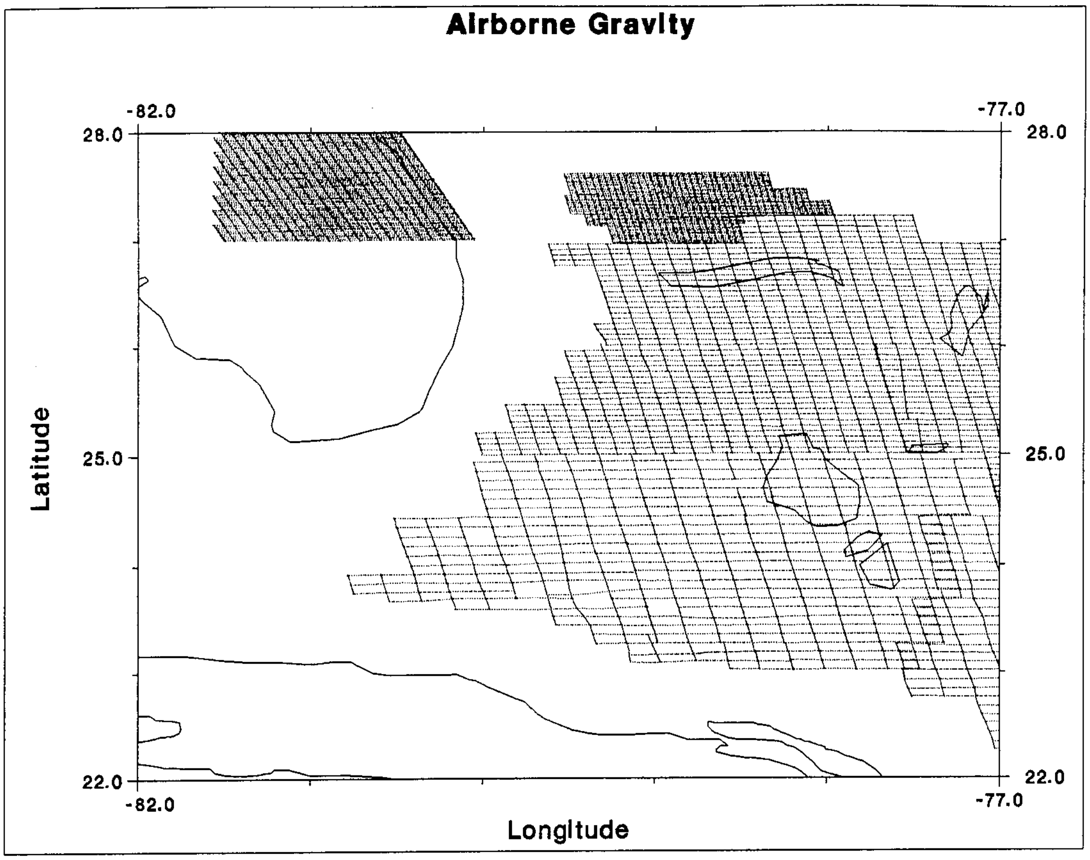

Figure 2: New Airborne Gravity Coverage

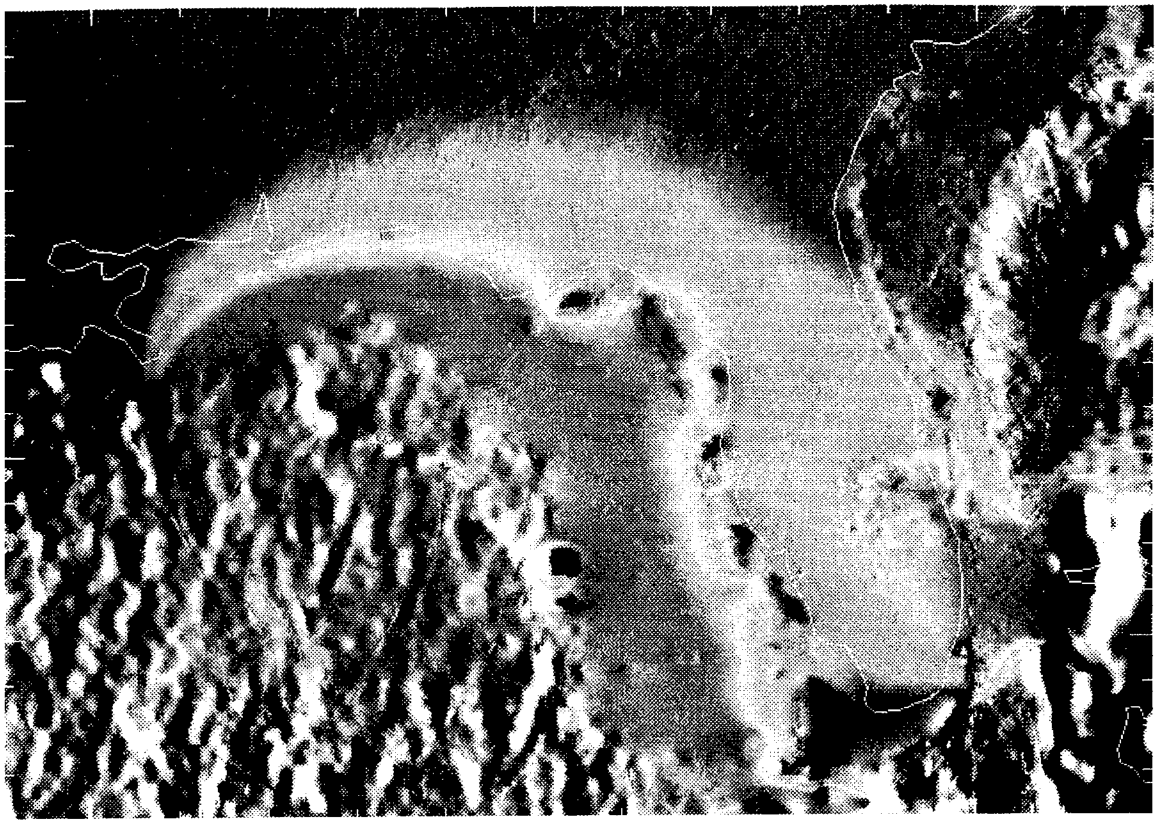

Figure 3: Differences between G96SSS and FLA98A (Magenta = 40 cm and lower, Red = 70 cm and higher)

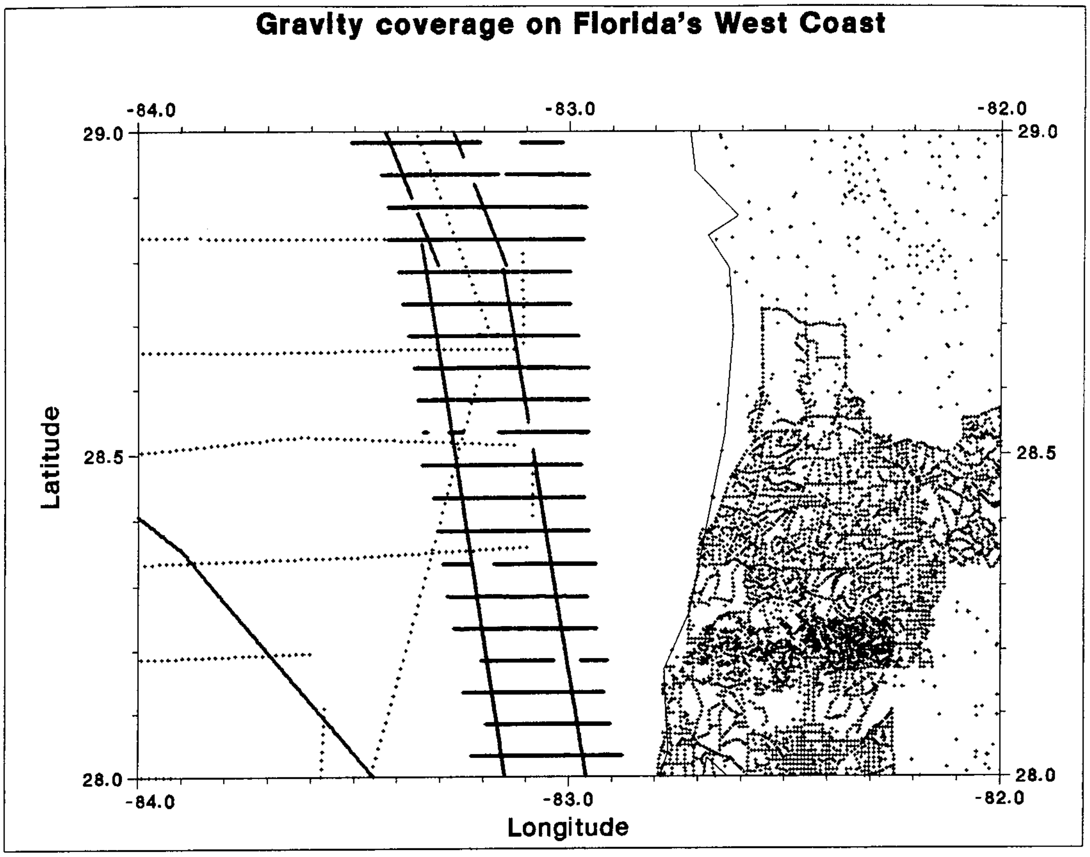

Figure 4: Gravity coverage on the northern West coast of Florida

APPENDIX B

Guidelines for Establishing Ellipsoid Heights Using the Global Positioning System (GPS)

Introduction

The starting point for the University of Florida (UF) research on the determination of ellipsoid heights with GPS was the National Oceanic and Atmospheric Administration (NOAA) - National Geodetic Survey (NGS) Technical Memorandum NOS NGS-58 "Guidelines for Establishing GPS Ellipsoid Heights (Standards : 2 cm and 5 cm)," [Zilkoski, 1997]. The NGS Guidelines rely primarily on the use of stations in the High Accuracy Reference Network (HARN), making only brief mention of the International Terrestrial Reference Frame (ITRF). The central role of the HARN stations immediately raises the question "are the vertical coordinates (ellipsoid heights) of the HARN stations sufficiently accurate to serve as reference stations for the determination of orthometric heights to two centimeters?" Based on the observing programs and the status of the GPS system when the Florida HARN was established, the answer may well be "no." And, even if the answer were to be "yes" the procedures developed by NGS are very complex, require six or more GPS receivers, and require several days of data collection. The primary goals of the UF research, sponsored by the Florida Department of Environmental Protection (FDEP) under the Governor's Innovation Program, and by the Florida Department of Transportation (FDOT) Research Center were to simplify the NGS Guidelines and reduce the observational requirements while maintaining or improving the accuracy of the ellipsoid heights obtained. The material presented in this brief document has been extracted from a more in-depth report by Carter and Shrestha [1998].

Reference Frames

The standard terrestrial reference frame used internationally for global scale geodetic positioning is the International Terrestrial Reference Frame (ITRF) developed and maintained by the International Earth Rotation Service (IERS). The ITRF is based on a combination of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and the Global Positioning System (GPS) networks. The GPS data analysis is performed by the International GPS Service for Geodynamics (IGS), which coordinates a global network of more than 100 permanently tracking GPS observatories well distributed around the globe. The IGS routinely distributes GPS satellite orbits accurate to the few centimeter level in a reference frame that is consistent with the ITRF and the earth orientation values, scale, and plate motion model adopted by the IERS. The GPS coordinates of most continuously operating IGS stations are consistent, in a relative sense, to one or two centimeters, however the entire reference frame may exhibit small changes in scale, translations and orientation with time that currently may still exceed a few centimeters.

In the United States the locations of survey markers or other objects are determined in a national reference frame, developed and maintained by the NGS, an Office within the National Oceanic and Atmospheric Administration (NOAA), Department of Commerce (DOC). Traditionally the NGS has maintained two separate networks, a horizontal network consisting of the geodetic latitudes and longitudes of survey markers, and a vertical network consisting of the heights of bench marks. Both of these networks were re-adjusted within the past two decades to produce the North American Datum of 1983 (NAD83) and North American Vertical Datum of 1988 (NAVD88).

The readjustment of the horizontal datum depended heavily on the Transcontinental Traverse (TCT) trilateration measurements and a relatively sparse network of Doppler Satellite positions. A few early VLBI observations were used to relate the NAD83 to the global reference frame then under development, but subsequent changes in the orientation, translation and scale of the ITRF have resulted in more than 2 meter differences in the X,Y,Z coordinates of stations expressed in the NAD83 and ITRF reference frames, mostly in the Y coordinate. Also, it is important to remember that the NAD83 coordinates are fixed while the ITRF coordinates change with time to reflect the effects of plate motion, glacial rebound and other earth dynamics. The relative coordinates of stations can change by up to 10 cm per year, and even more. The parameters to convert between ITRF and NAD83 coordinates have been determined by NGS and a computer program to compute the transformation values is also available from NGS.

After completion of the NAD83 the NGS began working, State by State, to develop High Accuracy Reference Networks (HARN) using GPS. Florida was the second state to have a HARN. The initial Florida HARN was completed in 1991. Stations were added to the Florida HARN in 1994. States generally do not work on a day-to-day basis with geodetic latitudes and longitudes, but rather with state plane coordinates. State plane coordinates are related to the national geodetic coordinates by well known mathematical equations and computer programs exist to transform coordinates from one system to the other.

GPS Role in Contemporary Surveying

As GPS has come of age, nearly all surveying (other than small parcel land title surveys) is now performed with this technology. GPS is the "method-of-choice" for the determination of X,Y,Z Cartesian coordinates, geodetic coordinates, and state plane coordinates. There are several reasons for the popularity of GPS for horizontal positioning: cost, accuracy, speed, and all weather global coverage. But GPS has not yet had a major impact on the determination of heights. The coordinates determined by GPS are essentially purely geometric which can be transformed rigorously into horizontal coordinates in the desired reference frame, and to geometric heights, such as geocentric height or ellipsoid height. Unfortunately, many engineering applications need heights above the geoid, an equipotential reference surface, and deriving orthometric heights from GPS observations requires a model of the geoid, which greatly increases the complexity of the problem. In addition, GPS is not as robust a technology for the determination of height, because the satellites can not be observed below the horizon, resulting in weaker geometry for the height determination. This report and associated guidelines deal with the issue of designing the observing program to assure that accurate geometric heights, specifically ellipsoidal heights, will reliably be obtained with GPS.

Continuously Operating Reference Stations (CORS)

Several organizations, most notably the US Coast Guard (USCG) and NGS, operate GPS receivers at fixed stations 24 hours a day 7 days a week. These stations are called CORS sites and are operated as a service to the users of differential GPS. The USCG stations were developed to serve the marine community and transmit corrections that enable mariners to correct pseudo range GPS observations to obtain higher accuracy positions in real time. The USCG stations also collect phase measurements that can be used in post processing for high accuracy differential phase GPS positioning. The NGS also has CORS stations to serve the geodetic surveying community by providing phase measurements for post processing of differential phase GPS observations. In addition, a number of other organizations including state agencies have or are planning to establish CORS sites, including the FDOT. Taking advantage of the CORS stations should result in very significant reductions in the number of stations that need to be occupied for specific surveys and associated savings in time and costs.

UF Guidelines for the Determination of Ellipsoid Heights with Precisions of 2 cm and 5 cm

Data Collection General Guidelines

1. All GPS observations collected for height determinations must be performed with dual frequency geodetic quality receivers using antenna types that have been calibrated for L1/L2 phase offsets with respect to the antenna radiation pattern (ARP) and for phase center variation (PCV). The use of choke ring antennas to suppress multi-pathing and fixed height tripods to reduce errors in measuring the antenna height above the mark and to make the height of the antennas above ground level more uniform throughout the project area, is strongly recommended.

2. Temperature to one degree centigrade and pressure to one millibar should be measured at at least one station withn the project or obtained from a weather station, such as the nearest airport. No humidity measurements are required.

3. The Vertical Dilution of Precision (VDOP) should be less than 5 throughout at least 75 percent of the observing period.

Data Collection Guidelines for 2 cm Ellipsoid Heights

1. If all of the stations within the project area, designated Project Stations (PS) are located less than 25 kilometers from a CORS station, data from the CORS site can be used directly to reduce the project observations, without establishing the Project Control Stations (PCS) discussed below in paragraph 2.

2. If any PS is further than 25 kilometers from a CORS site, it is necessary to establish one or more Project Control Stations (s), PCS, at a location (s) that will result in all PS being within 25 kilometers (station to station vector length) of a CORS or a PCS.

3. Each PCS will be observed a minimum of one 24 hour continuous period, or two 12 hour periods, or 3 eight hour periods, using an observing data log rate of 30 seconds or less. The observing period(s) will cover the full observing periods for all PS, to facilitate the computation of vectors from each PS directly to a CORS or PCS.

4. Each PS more than 5 kilometers from a CORS or PCS will be observed for at least two 1.5 hour periods using an observing data log rate of 30 seconds. The two observing periods must be separated by a minimum of 4 hours within the GPS day, in order to use different satellites and obtain significantly different geometry.

5. Each PS within 5 kilometers of a CORS or PCS may be observed for only one 90 minute period with an observing data log rate of 30 seconds. Or, the observing period may be compressed by using a shorter observing interval. For a 15 second interval the acceptable observing period is 45 minutes, for a 5 second interval a period of 15 minutes. Note: the CORS or PCS station used to reduce the PS observations must collect data at least as often as the shortest interval used at a PS. If the optional short observing sessions at 15 and 5 seconds intervals are used, the observing session must be repeated at a GPS time differing by 90 minutes, and the results of the two sessions must agree to within 2 centimeters in ellipsoid heights or additional observing sessions must be made until such agreement among sessions used to meet the minimum required observing periods is fulfilled.

Processing of the GPS Data (2 cm)

1. All vectors originating at CORS and PCS sites and terminating at PS sites will be computed using geodetic quality computer software, such as NGS Page4, using precise orbits obtained from NGS or another IGS Center.

2. The data reduction must include corrections for antenna phase center variations.

3. Only observations with zenith distances less than 75 degrees (satellite altitudes greater than 15 degrees) should be included in the final solution. The final solution for each vector should have a minimum of 160 acceptable epochs with a minimum of 5 satellites and the integer cycles should be fixed, when possible.

4. Ellipsoid heights determined from repetitive sessions at PCS and PC must agree within a total spread of 2 cm, or additional observing sessions must be made until such agreement among sessions used to meet the minimum required observing periods is fulfilled.

Data Collection Guidelines for 5 cm Ellipsoid Heights

1. If all of the stations within the project area, designated Project Stations (PS) are located less than 50 kilometers from a CORS station, data from the CORS site can be used directly to reduce the project observations, without establishing the Project Control Stations (PCS) discussed below in paragraph 2.

2. If any PS is further than 50 kilometers from a CORS site, it will be necessary to establish one or more Project Control Stations (s), PCS, at a location (s) that will result in all PS being within 50 kilometers (station to station vector length) of a CORS or a PCS.

3. *Each PCS will be observed a minimum of one 12 hour continuous period, or two 6 hour periods, or three 4 hour periods using an observing interval (data log rate)l of 30 seconds or less. The observing period(s) will cover the full observing periods for all PS, to facilitate the computation of vectors from each PS directly to a CORS or PCS.

4. Each PS more than 10 kilometers from a CORS or PCS will be observed for at least one 90 minute period using an observing interval (data log rate) of 30 seconds.

5. Each PS within 10 kilometers of a CORS or PCS may be observed for at least one 90 minute period with an observing interval of 30 seconds. Or, the observing period may be compressed by using a shorter observing interval. For a 15 second interval the acceptable observing period is 45 minutes, for a 5 second interval a period of 15 minutes. Note: the CORS or PCS station used to reduce the PS observations must collect data at least as often as the shortest interval used at a PS. If the optional short observing sessions at 15 and 5 seconds intervals are used, the observing session must be repeated at a GPS time differing by 90 minutes, and the results of the two sessions must agree to within 5 centimeters or additional observing sessions must be made until such agreement among sessions used to meet the minimum required observing periods is fulfilled.

Processing of the GPS Data (5 cm)

1. All vectors originating at CORS and PCS sites and terminating at PS sites will be computed using geodetic quality computer software, such as NGS Page4, using precise orbits obtained from NGS or another IGS Center.

2. The data reduction must include corrections for antenna phase center variations.

3. Only observations with zenith distances less than 75 degrees (satellite altitudes greater than 15 degrees) should be included in the final solution. The final solution for each vector should have a minimum of 160 acceptable epochs with a minimum of 5 satellites and the integer cycles should be fixed, when possible.

4. Ellipsoid heights determined from repetitive sessions at PCS and PC must agree within a total spread of 5 cm, or additional observing sessions must be made until such agreement among sessions used to meet the minimum required observing periods is fulfilled.

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Acknowledgments

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